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Low friction and wear resistant coatings

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INTRODUCTION

In industrialised societies there is an increasing demand to reduce or control friction and wear of engineering materials. The principal impetus behind this endeavour is related to economical and environmental aspects. The needs to extend the efficiency of machinery, to optimise energy consumption, to conserve scarce material resources and to reduce the use of hazardous lubricants, are just a couple of examples.

In the first half of the twentieth century these aims have been achieved by improving the bulk material, or by refining the lubrication techniques. For a tool to be able to resist wear it must have a high hardness and temperature strength, be chemically stable and possess a high toughness.¹ In order to reduce friction, it must be capable of forming a stable compound at the contact interface to control the ensuing friction and wear behaviour.²

As is generally recognised, it is impossible to combine all these properties together in a single conventional tool material. However, nowadays, composite and surface-engineered materials are developed so as to tailor desired material properties for a specific application. A large variety of functional properties can be optimised separately for the bulk material and the surface by applying an appropriate coating. Depending upon the application, a substrate-coating combination or composite system can be selected. For example, in cutting tools, the bulk material is chosen to provide the toughness while the coating is responsible for the resistance to wear and for the reduction of friction.

In the last three decades surface engineering has become an enabling field of science and technology. The first coatings were mainly deposited electrochemically. However, the coating hardness obtained by this technique was far from improving significantly the uncoated work-pieces. With the introduction of the chemical vapour deposition (CVD) process, and later through the evolution of physical vapour deposition (PVD) techniques with both sputtering and evaporative sources, this field has become more mature.^{3,4} Typical coating materials in these categories are refractory borides, carbides, nitrides, oxides, as well as their combinations.

The PVD coatings have certain microstructural advantages over their CVD counterparts. The PVD films are extremely fine grained and individual crystallites contain a large concentration of point defects due to the non-equilibrium deposition process.⁵ In contrast, CVD films are generally formed under thermal equilibrium, resulting in high-angle grain boundaries and grain sizes in the range of 0.5 to 5 μm .⁶ Consequently, PVD coatings are consistently harder than CVD coatings. Another important factor is the level of residual stress in the coating. A PVD coating shows a high compressive stress, whilst those formed by CVD are under a relatively low tensile stress.⁷ The compressive residual stress in the plane of a coating improves the surface fracture strength or toughness of the coated tool.⁸ In addition, the lower deposition temperature used in PVD over CVD processes leaves the stress state of the substrate unaffected, whilst the CVD process anneals out any beneficial compressive stresses present in the uncoated tool.⁹

This thesis is focused on the most promising low friction and wear resistant PVD coatings that are available these days. Tungsten carbide-carbon (WC/C) multilayer coatings, by uniquely combining the properties of diamond-like carbon (DLC) and tungsten carbide, are evaluated for tribological applications. This uniqueness can be attributed to their high elasticity, chemical inertness, low static and dynamic friction coefficients coupling with metals and ceramics, and high wear resistance.¹⁰ An important area of application lies in dry lubrication of sliding contacts with high contact stresses under conditions where fluid lubrication is beset with difficulties, e.g. at high and low pressures, high and low temperatures and slow oscillations.¹¹ In these cases, the surfaces are coated with a thin low friction and low wear rate solid lubricant.

The application of hard TiN coatings to metal cutting tools has been hailed as one of the most significant technological advances in the development of modern tools. Although cutting tools have been the primary target for the development of such coatings, TiN has also found other tribological applications, such as in bearings, seals and as an erosion protection layer. Another important attraction of TiN is its potential application in microelectronics.¹² Finally, the golden colour has also encouraged applications as decorative coatings.

The TiN/(Ti,Al)N multilayer is part of an emerging class of new hard protecting coatings based on the homogeneous TiN. The concept of coatings composed of a large number of thin layers of two or more different materials, has shown to provide an improvement of the performance over comparable single layers.¹³ In the present case, the multilayer combines, among others, the high oxidation resistance of (Ti,Al)N at higher temperatures with the good adhesion of TiN to the substrate. Additionally, the introduction of a number of interfaces parallel to the substrate surface can act to deflect cracks or provide barriers to dislocation motion, increasing the fracture resistance of the coating.¹⁴ Consequently, the wear resistance of cutting tools, especially at high speed, is enhanced.

Regardless of the coating-substrate composites undoubted success, they are often poorly characterised and badly understood. Clearly, if significant input is to be made in the design of improved coatings, a detailed knowledge of the relationship between the microstructure and mechanical properties is essential. Further, as multilayer coatings are materials engineered on the nanoscale, it is necessary to carry out a fundamental study of the interactions between each layer at this scale in order to describe their wear mechanisms and tribological properties.

This thesis aims at contributing to the ongoing effort of understanding the low friction and wear resistant coatings. The focus is on a thorough characterisation of the microstructure and mechanical properties. Additionally, a detailed study of the fracture mechanisms is performed by nanoindentation and rolling contact fatigue tests, allowing to predict how the coated systems will perform in service.

CHAPTER 1

The outline of the thesis is as follows: chapter 2 provides the information regarding the coatings deposition techniques and the methods utilised for their characterisation; chapter 3 concentrates on the microstructure of WC/C multilayers, while chapter 4 presents their mechanical properties and wear behaviour; chapter 5 describes a parallel study of the microstructure of TiN and TiN/(Ti,Al)N multilayers; chapter 6 is also dedicated to TiN-based coatings, but here discussing their mechanical properties and wear behaviour.

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